

# **Residual Strength Characterization of Unitized Structures Fabricated Using Different Manufacturing Technologies**



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- **Built-up and Integral Structures**
- **Development of Prediction Methodology for Integral Structures Fabricated using different Manufacturing Procedures**
- **Testing Facility**
- **Fracture Parameters Definition**
- **Crack Branching in Integral Structures**
- **Results and Discussion**
- **Concluding Remarks**

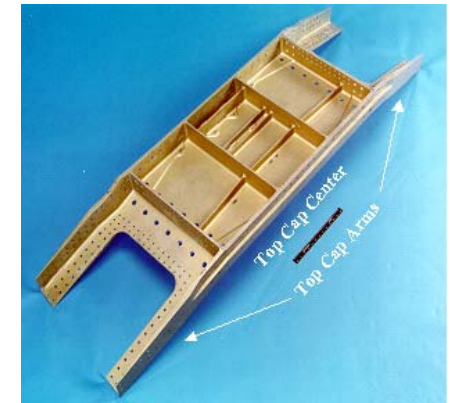
# Built-up and Integral Structures



- **Built-up structure**
  - Expensive & time intensive manufacturing & assembly
  - Difficult to inspect
  - Sites for crack initiation
- **Integral Structure**
  - Reduced assembly
  - Reduced initiation sites
  - Damage containment features
  - Effected by residual stress



**Built-up panel**



**Integral panel**

## Integral types:

- Machined (forged/extruded then machined to final form)
- Near net shape
- Joined



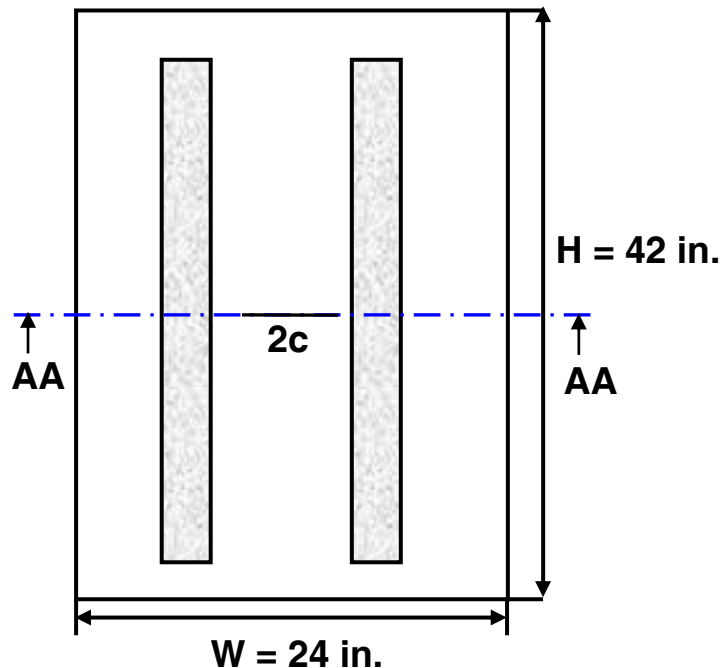
**E-beam fabrication**

# Development of Prediction Methodology for Damage Tolerance Certification of Integral Structures

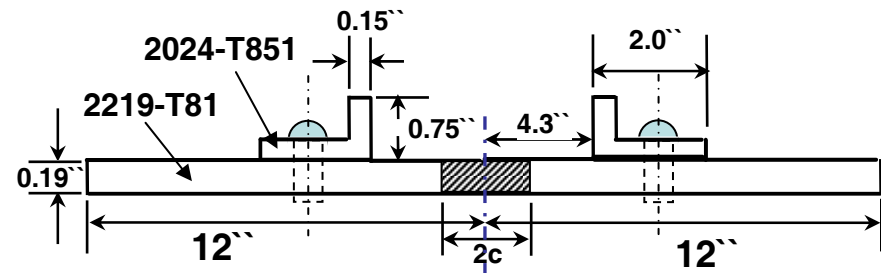


## Different Manufacturing Procedures Analyzed

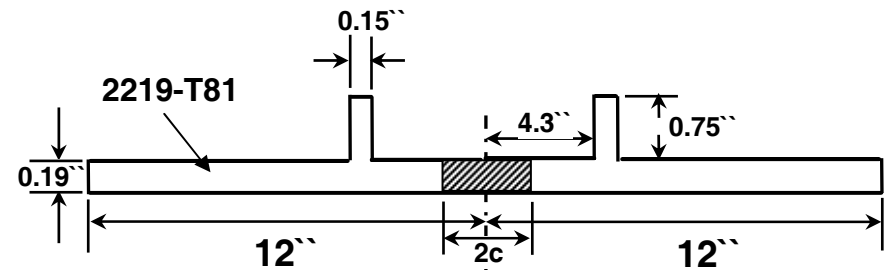
### 24-inch wide integrally stiffened panel



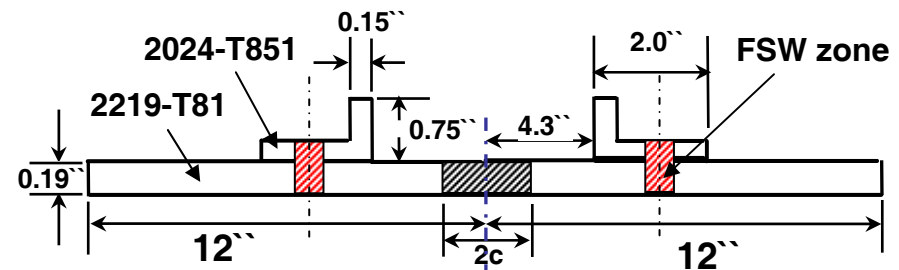
### Built-up



### Integrally machined, Free form & Extruded



### Friction stir weld (FSW)



**Objective: Need robust analytical method to characterize these varying configurations.**

# Testing Facility



**300 kip test facility**

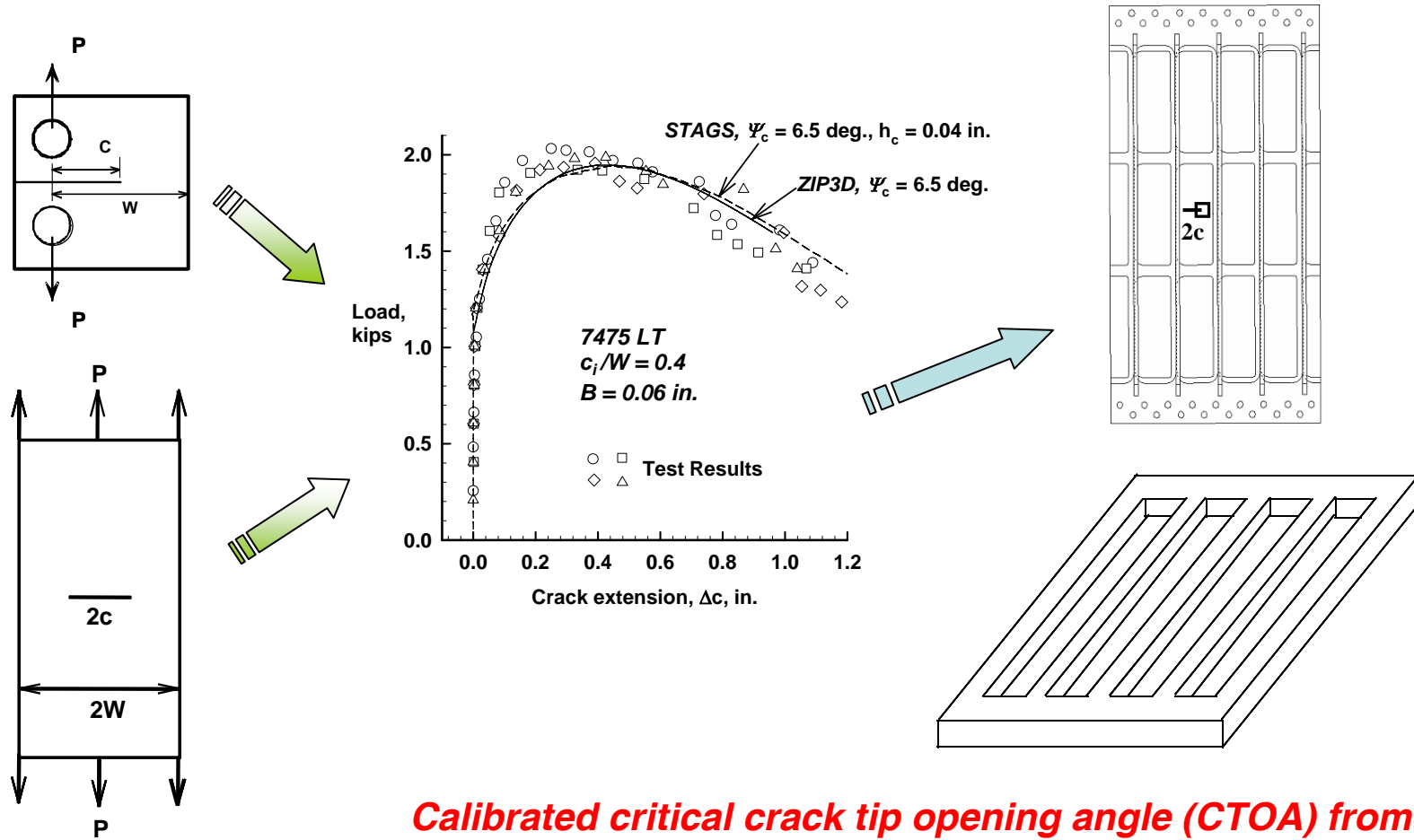


**A typical panel test setup**



# Prediction Methodology

## Coupon data utilized to predict the residual strength



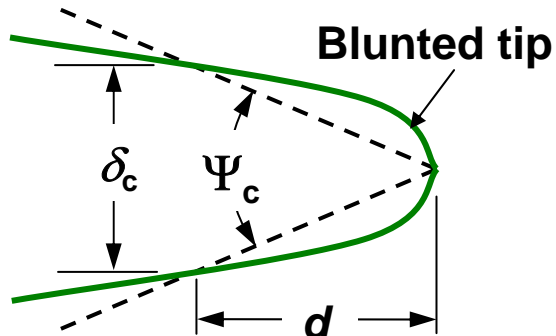
**Calibrated critical crack tip opening angle (CTOA) from coupon tests used in ZIP3D and STAGS analysis**

# **Analysis of Built-up and Integral Structures using CTOA Concept**



- **As part of earlier aging aircraft program, 40-inch and 12-inch wide built-up stiffened and unstiffened panels with and without multi-site-damages (MSDs) were successfully analyzed for residual strength using CTOA concept.**
- **As part of aircraft-structural integrity program (ASIP), large curved built-up panels were analyzed for residual strength under pressure loading.**
- **40-inch wide flat integrally stiffened thin panels with initial crack were analyzed for residual strength.**
- **48-inch wide curved integrally stiffened panel was analyzed for residual strength under the combination pressure and tensile loading.**
- **20-inch wide integrally stiffened Alcoa thick panels were analyzed for residual strength.**
- **C(T) and M(T) specimens of various thicknesses and materials have been successfully tested and analyzed using CTOA concept.**

## Crack Tip Opening Angle, $\Psi_c$ (CTOA)

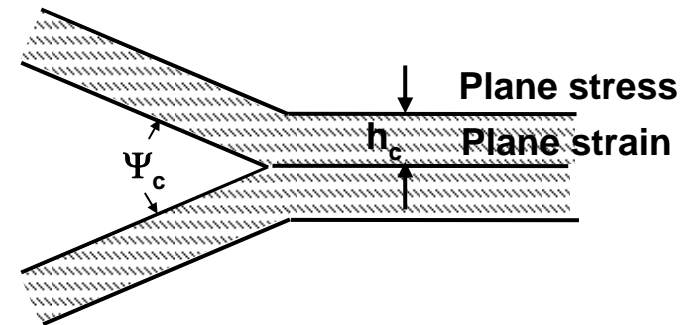


$\delta_c$  - Opening displacement

$\Psi_c$  - Measured at a fixed distance  $d$   
behind the moving crack tip

$$\Psi_c = 2 \tan^{-1} \left( \frac{\delta_c}{2d} \right)$$

## Plane strain core height, $h_c$



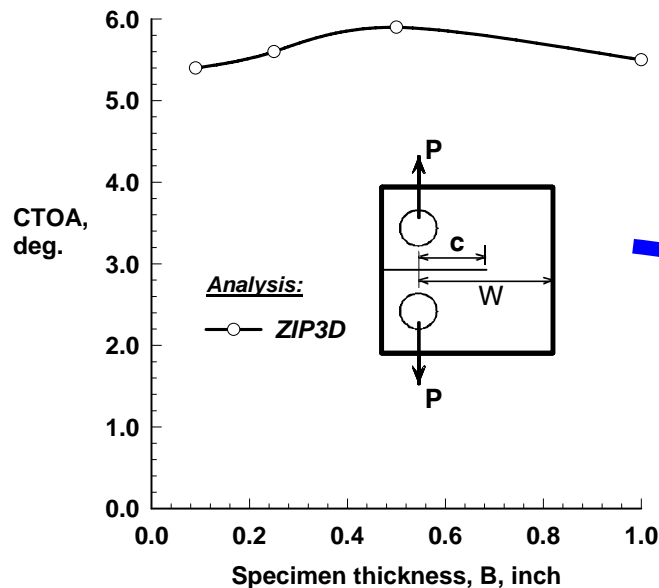
- $\Psi_c$  is a function of material and thickness



# Schematic Representation of Crack Branching with CTOA Criterion

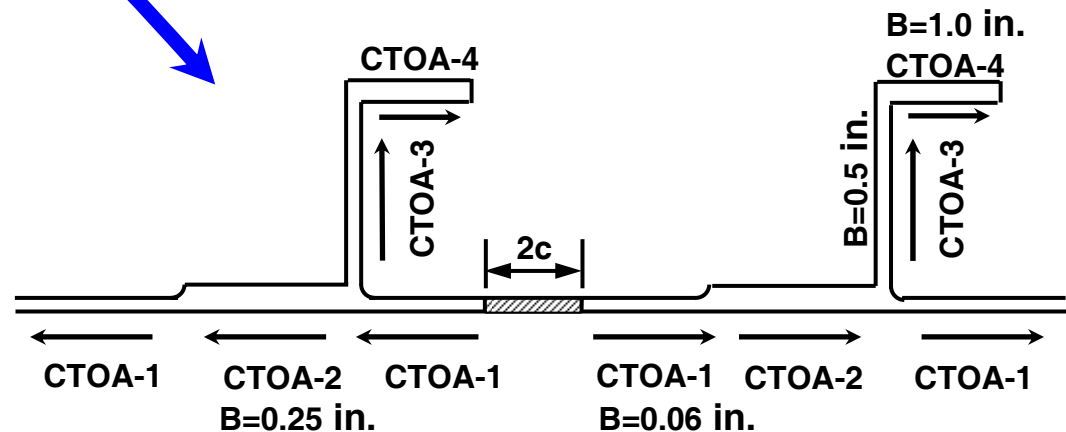


1. Develop CTOA vs. thickness relationship using mechanical test specimen data.



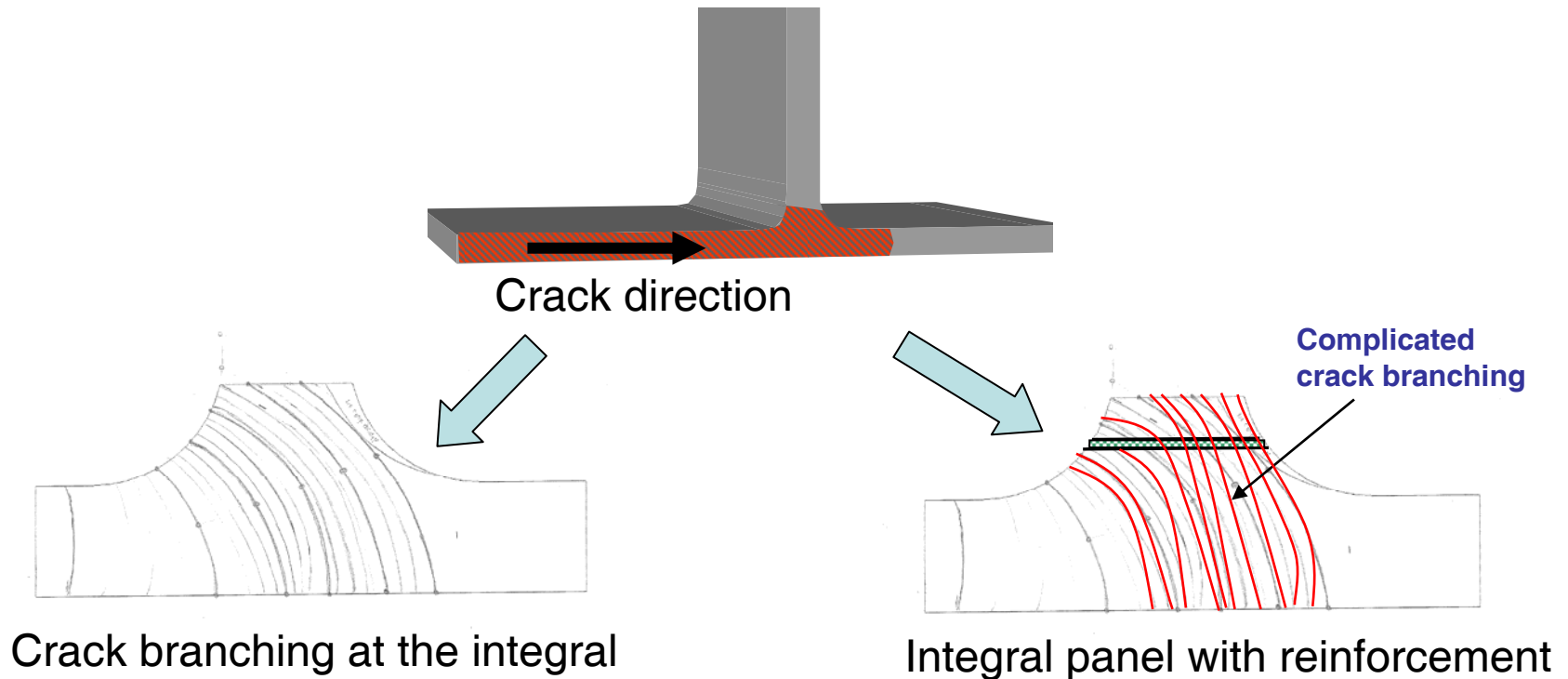
Variation in critical CTOA with specimen thickness

2. Analyze each section of an integrally stiffened panel using the appropriate CTOA.



Crack extends through sections of various thicknesses in the integrally stiffened panel

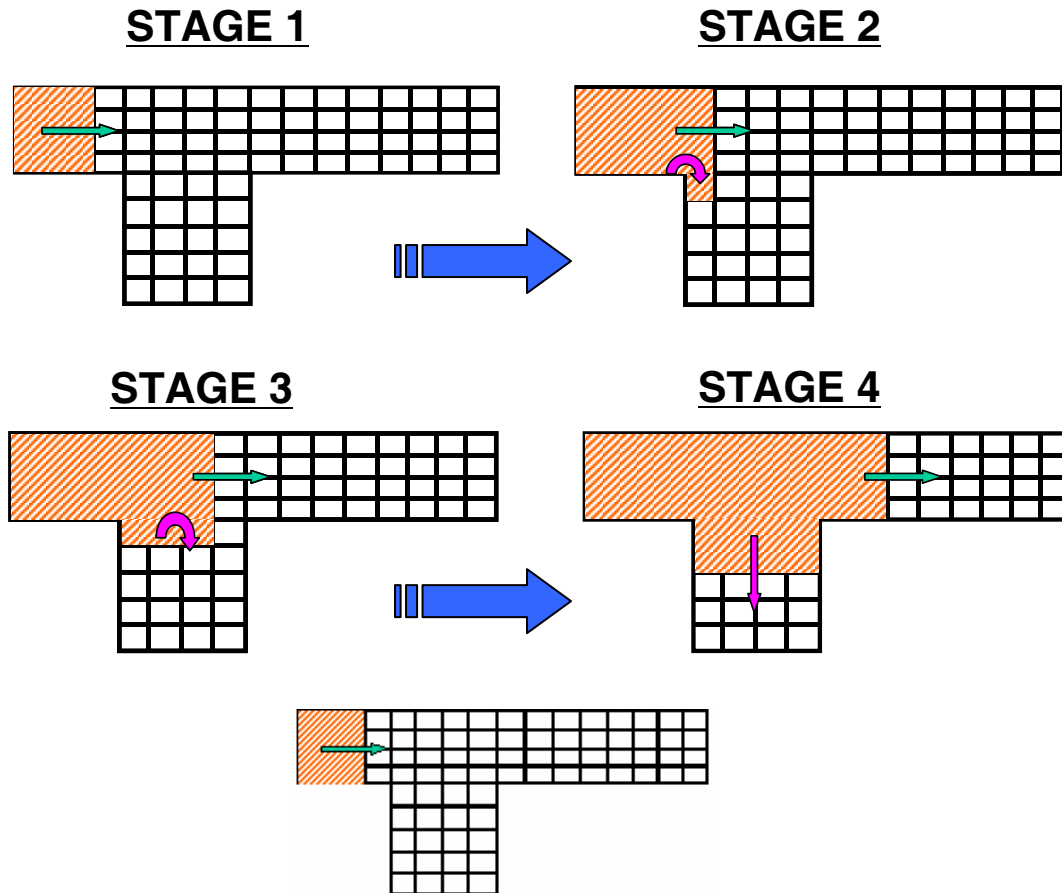
# Crack Branching in Integral Structures



- **Effects of crack tip plasticity, three dimensional constraints around a crack tip addressed.**
- **Crack branching process - not well understood.**
- **Crack growth in reinforced sections – not been fully realized.**

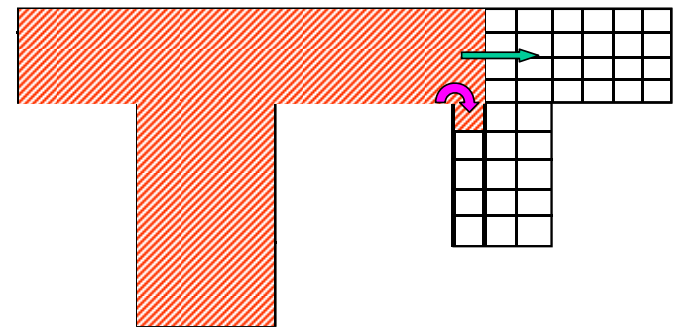
# Different Stages in Crack Branching

## Crack growth simulation



## General scenario

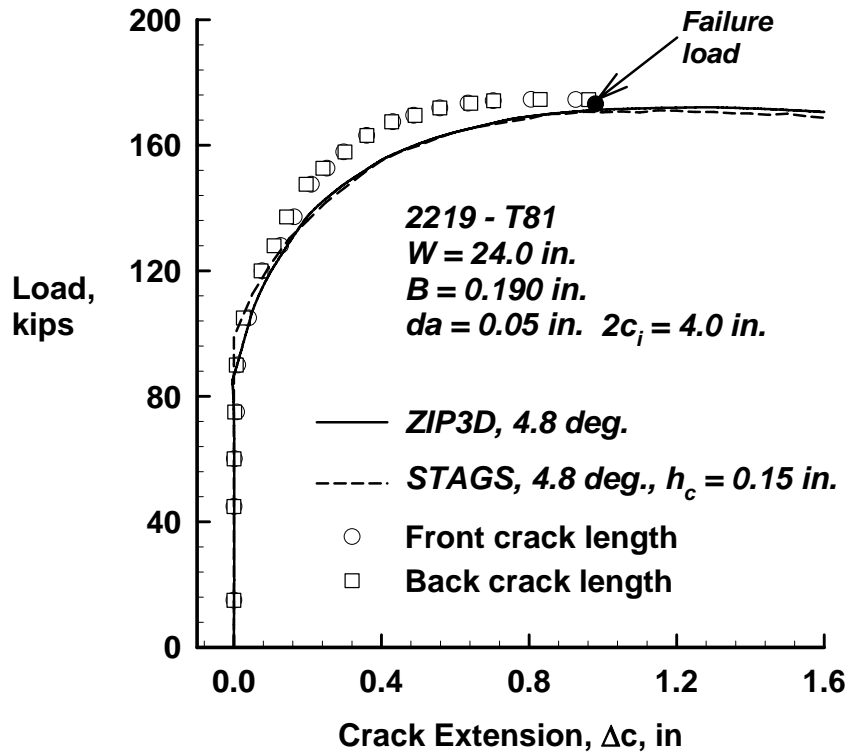
Lead crack branching into multiple integrals of various thickness



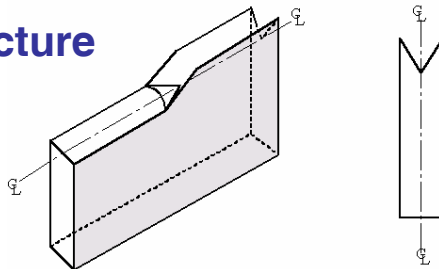
# Load Crack Extension data for 24-inch Wide Unstiffened M(T) Panel



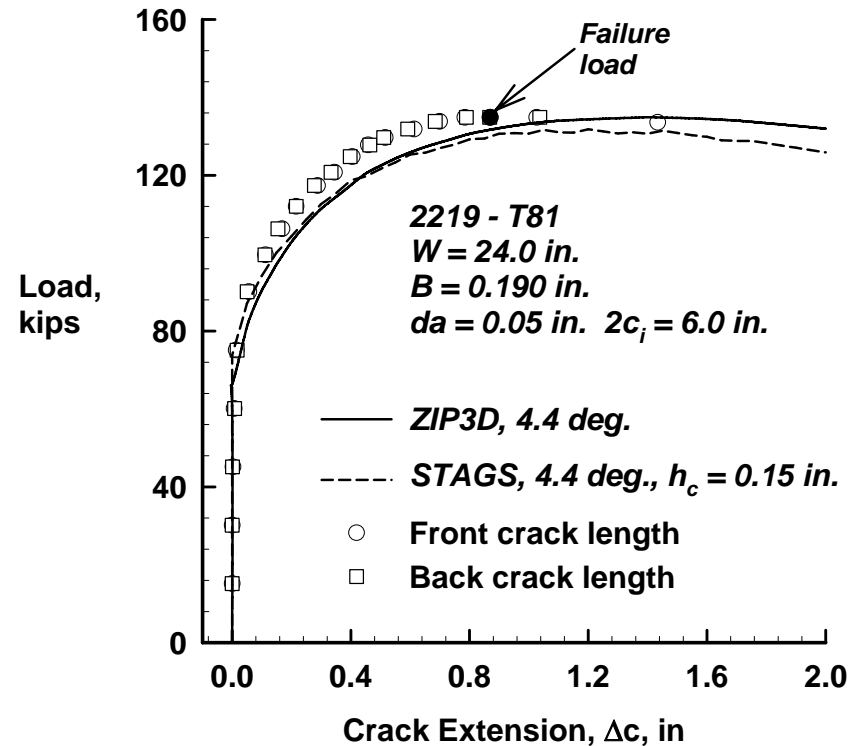
**Panel-1**



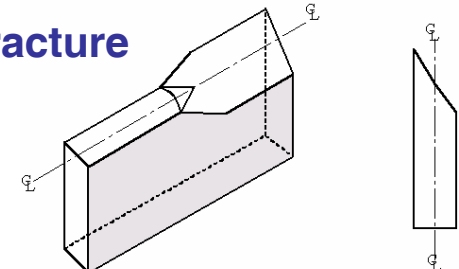
**V- fracture**



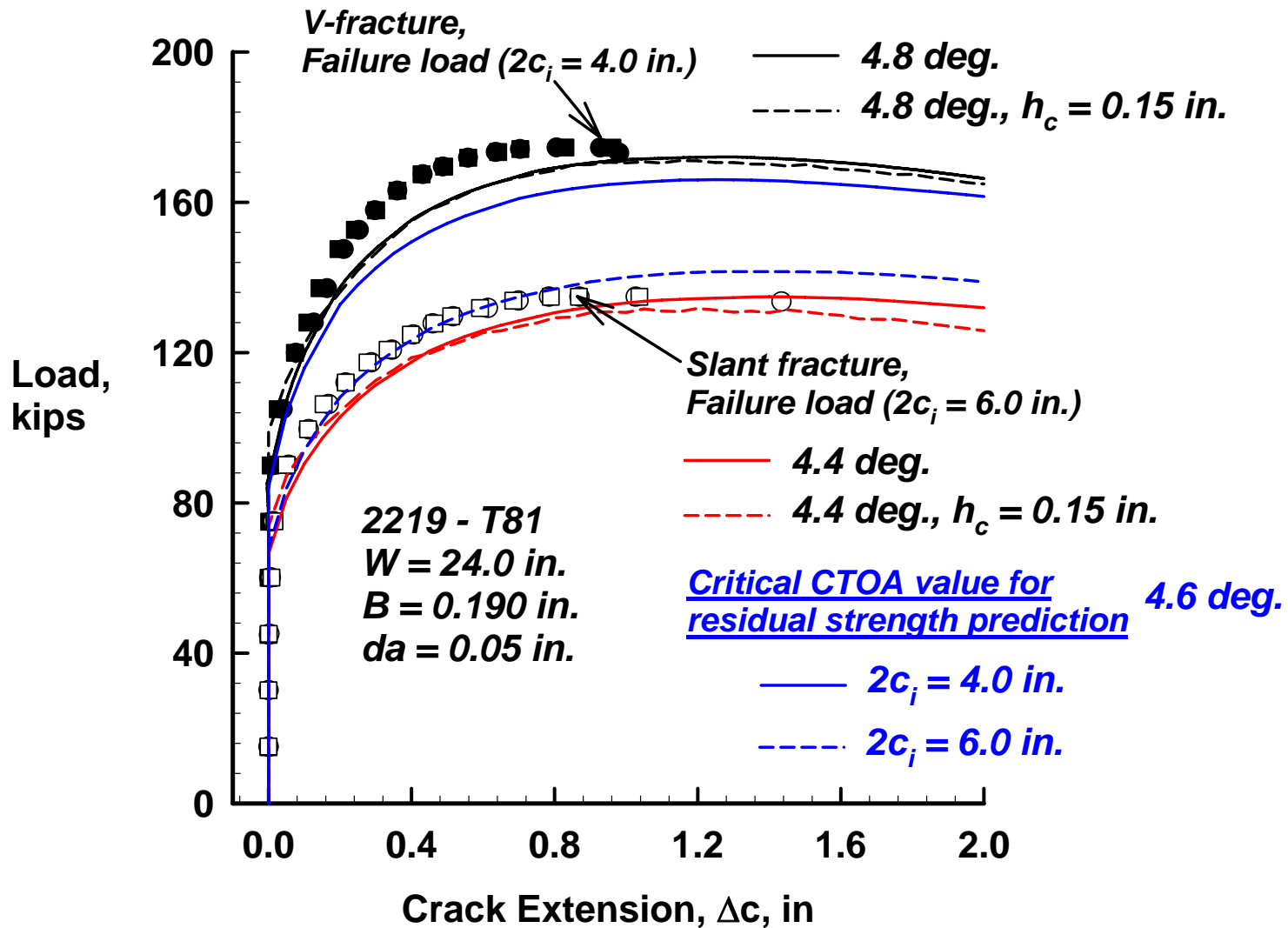
**Panel-2**



**Slant fracture**



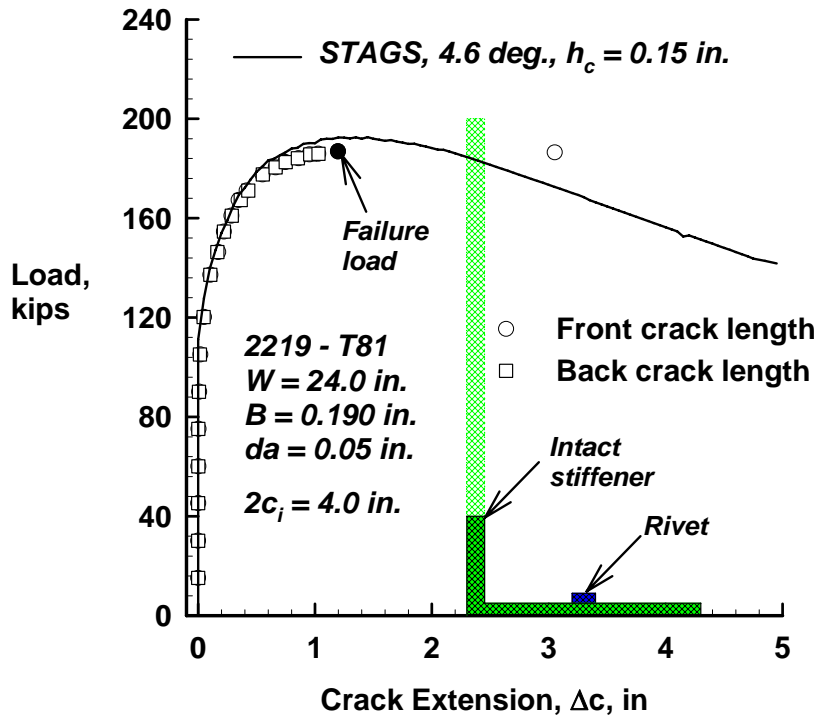
# Load Crack Extension data for 24-inch Wide Unstiffened M(T) Panel



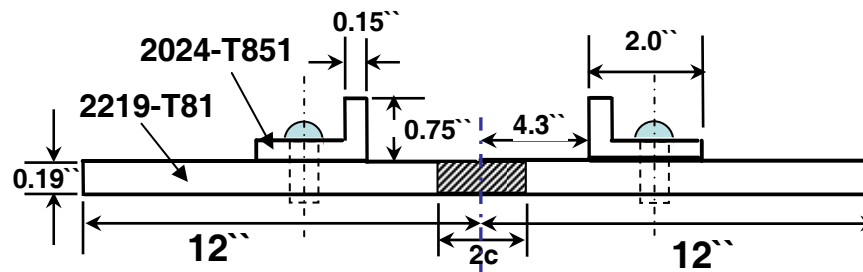
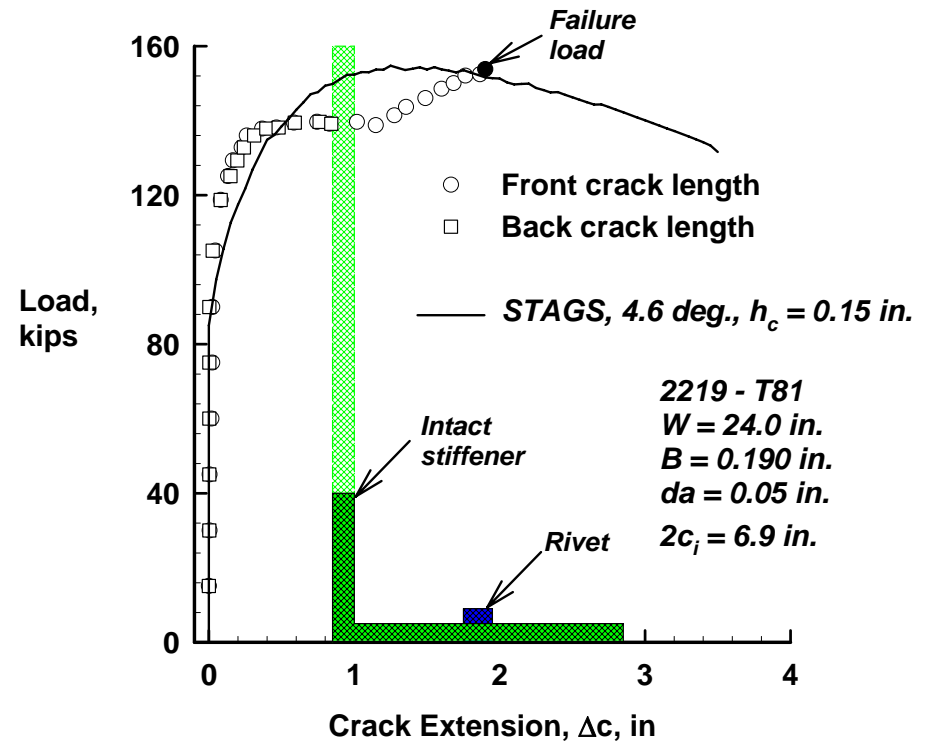
# Load Crack Extension data for 24-inch Wide Built-up Panel



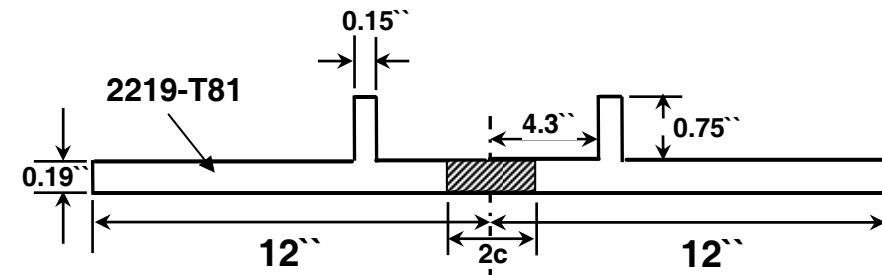
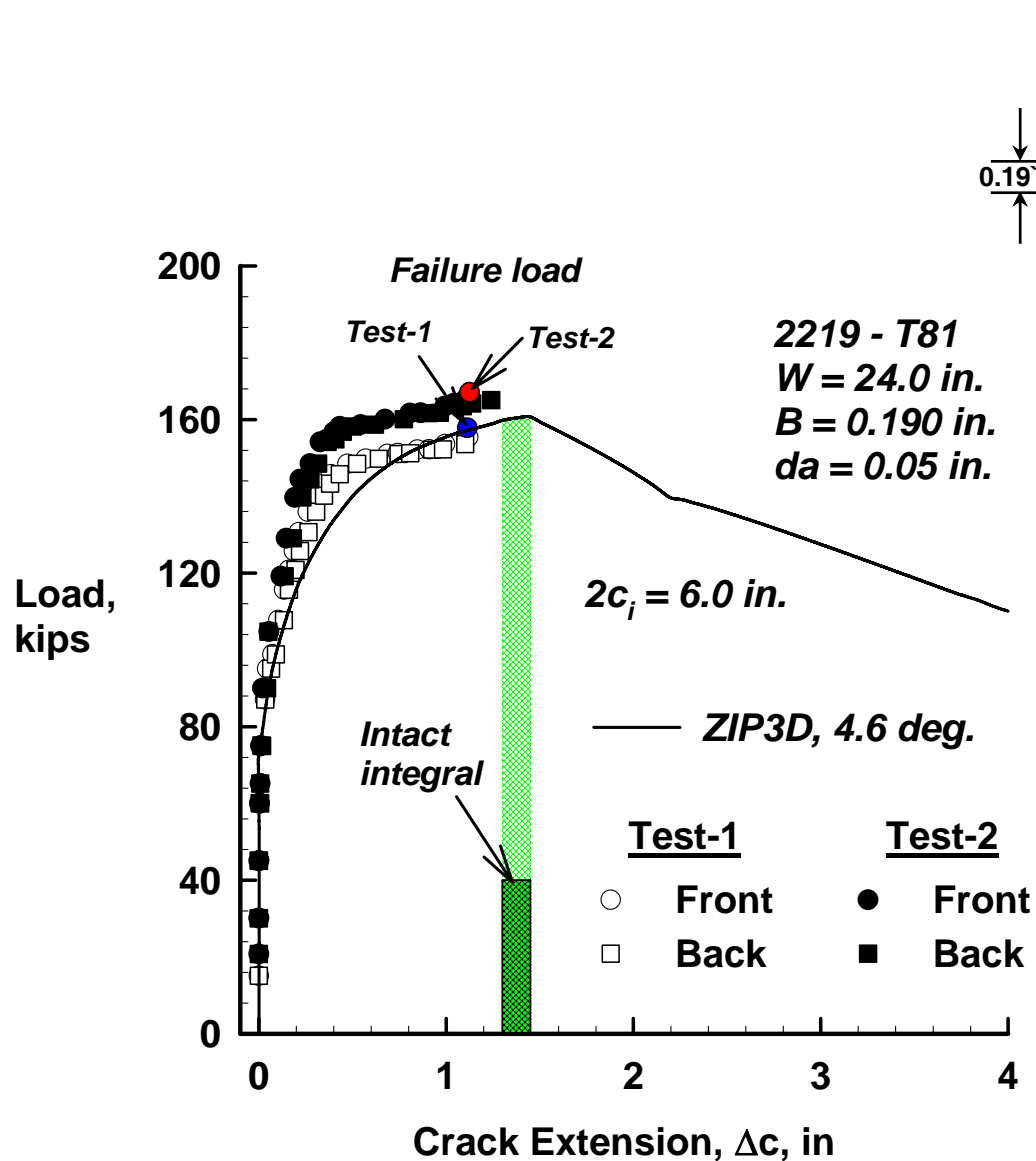
**Panel-1**



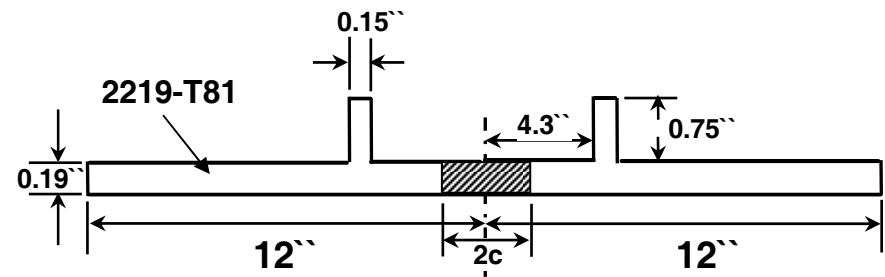
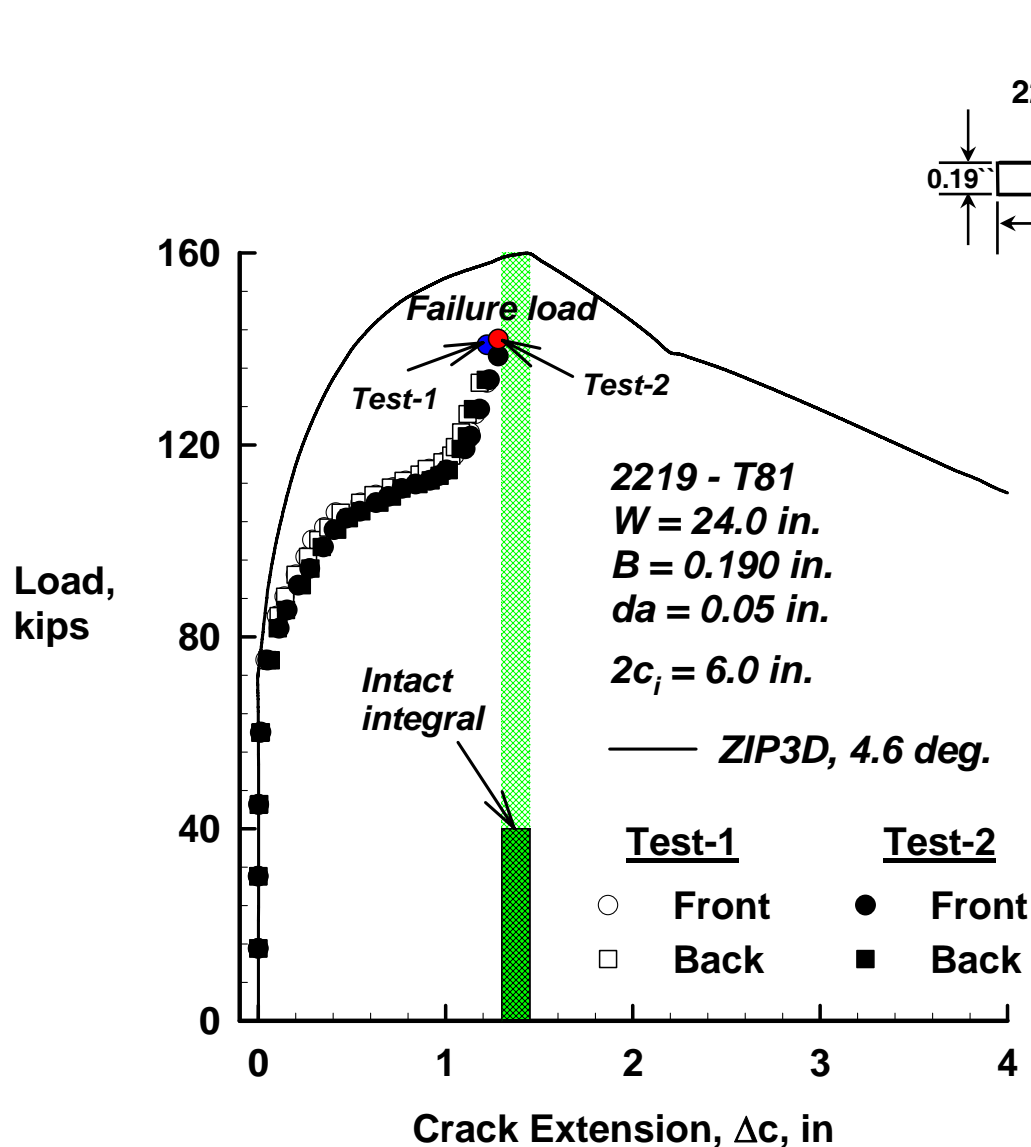
**Panel-2**



# Load Crack Extension data for 24-inch Wide Integrally Machined Panel

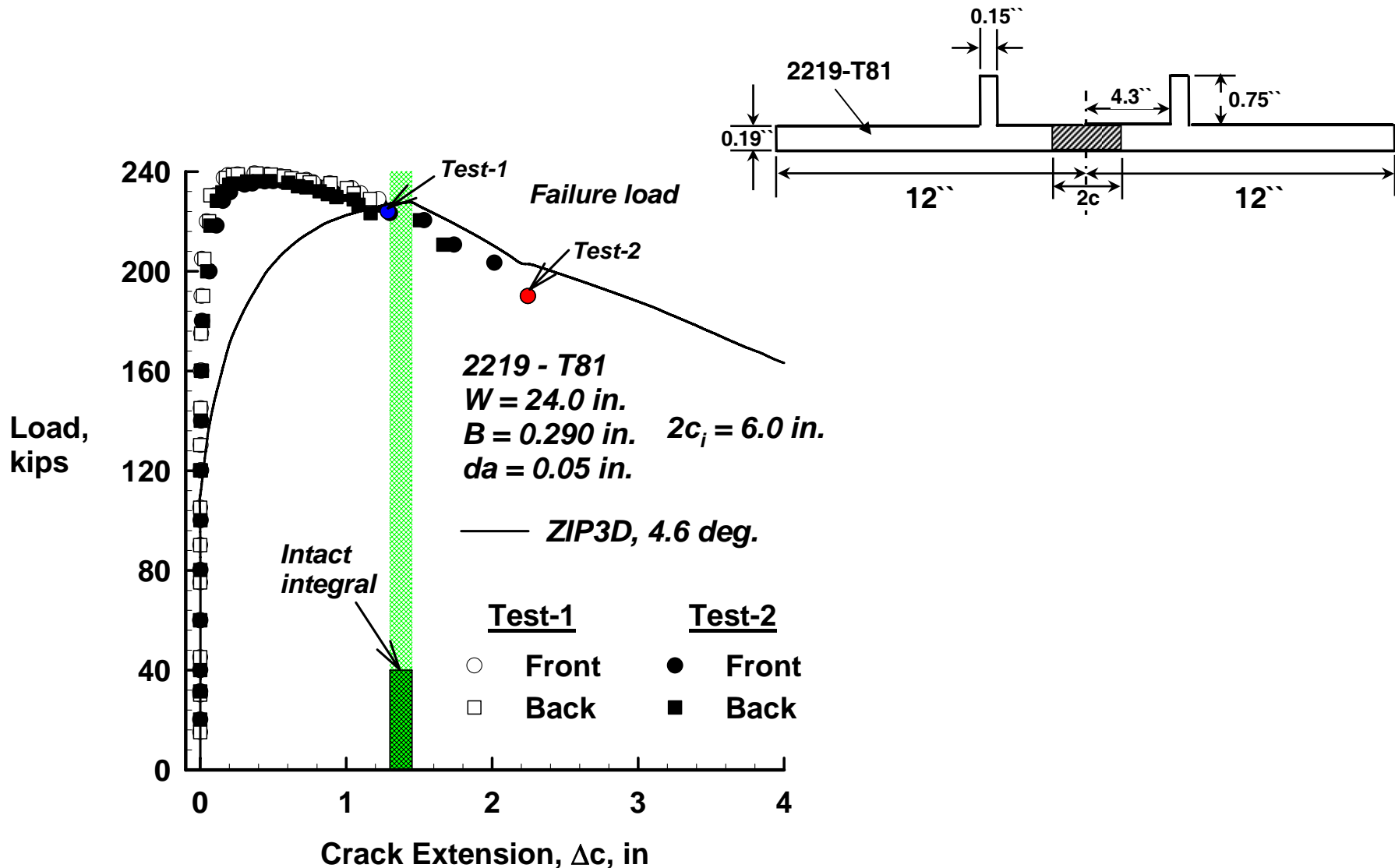


# Load Crack Extension data for 24-inch Wide Free Form Panel

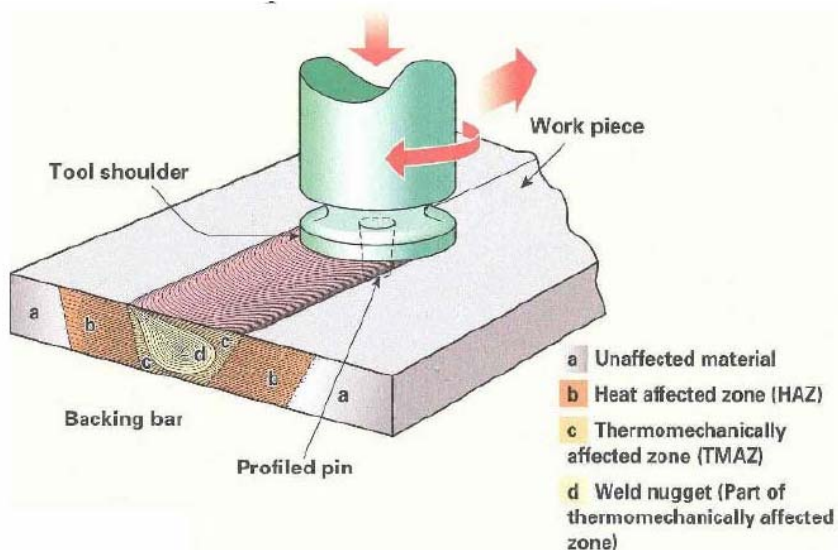




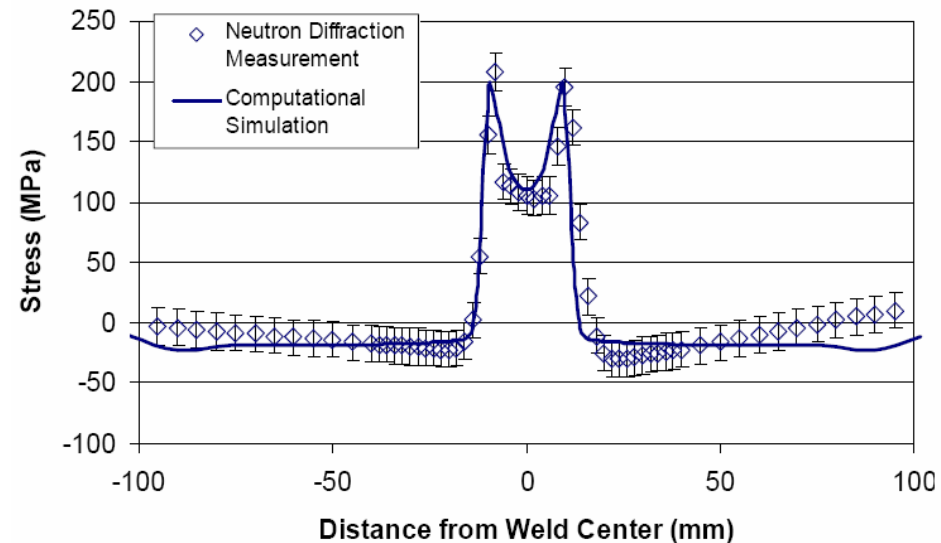
# Load Crack Extension data for 24-inch Wide Extruded Panel



# Friction Stir Welding of Advanced Materials

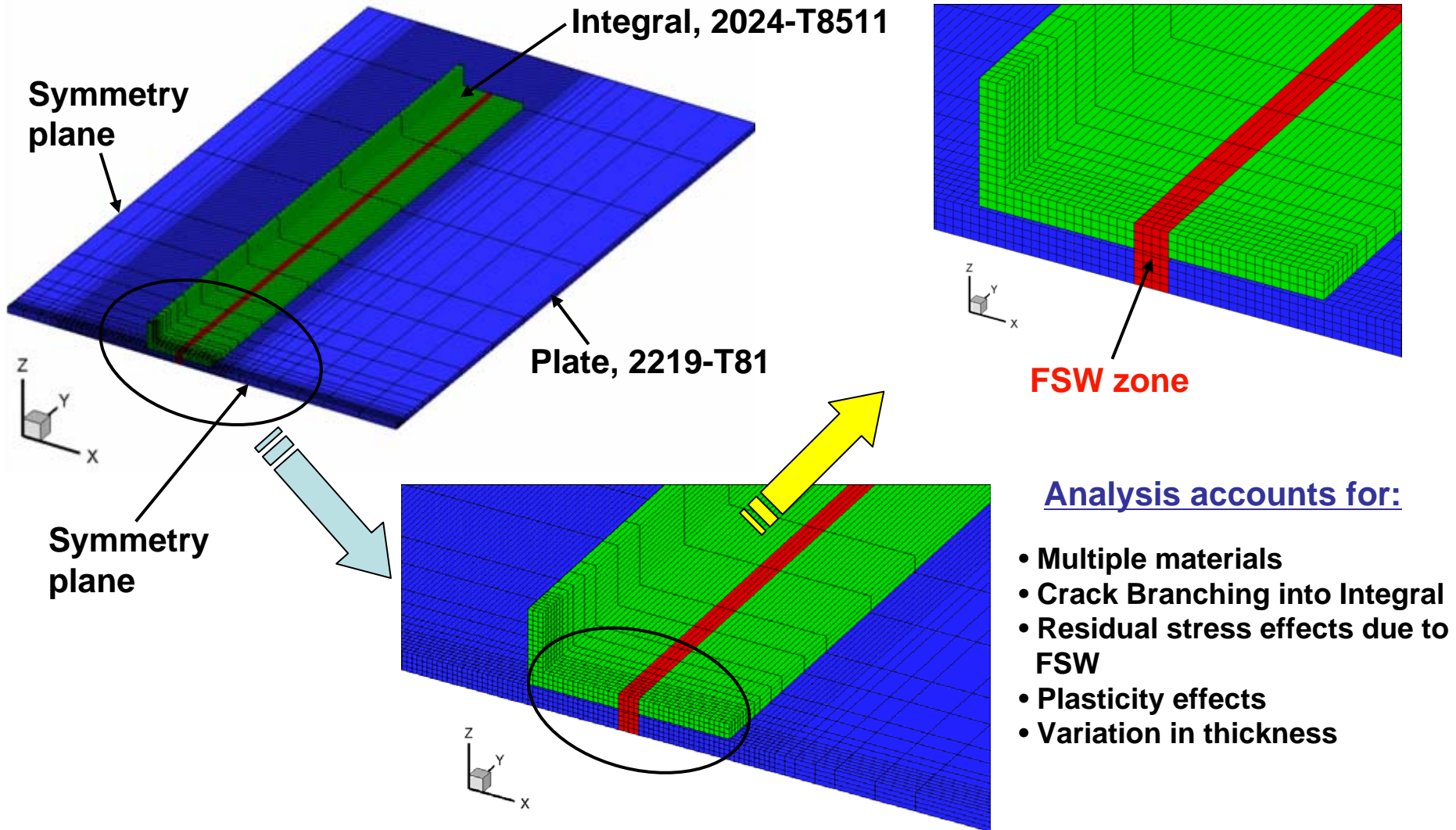


**Schematics of Friction Stir Welding Process**

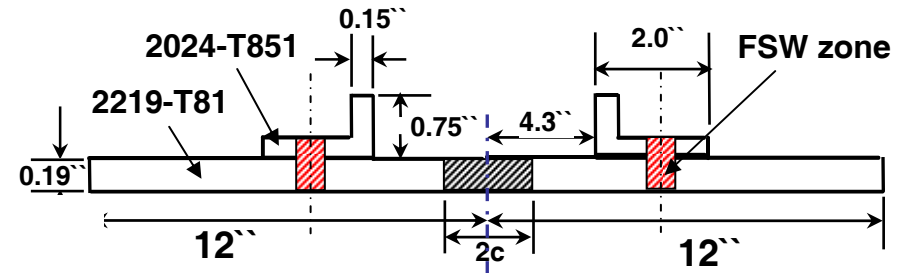
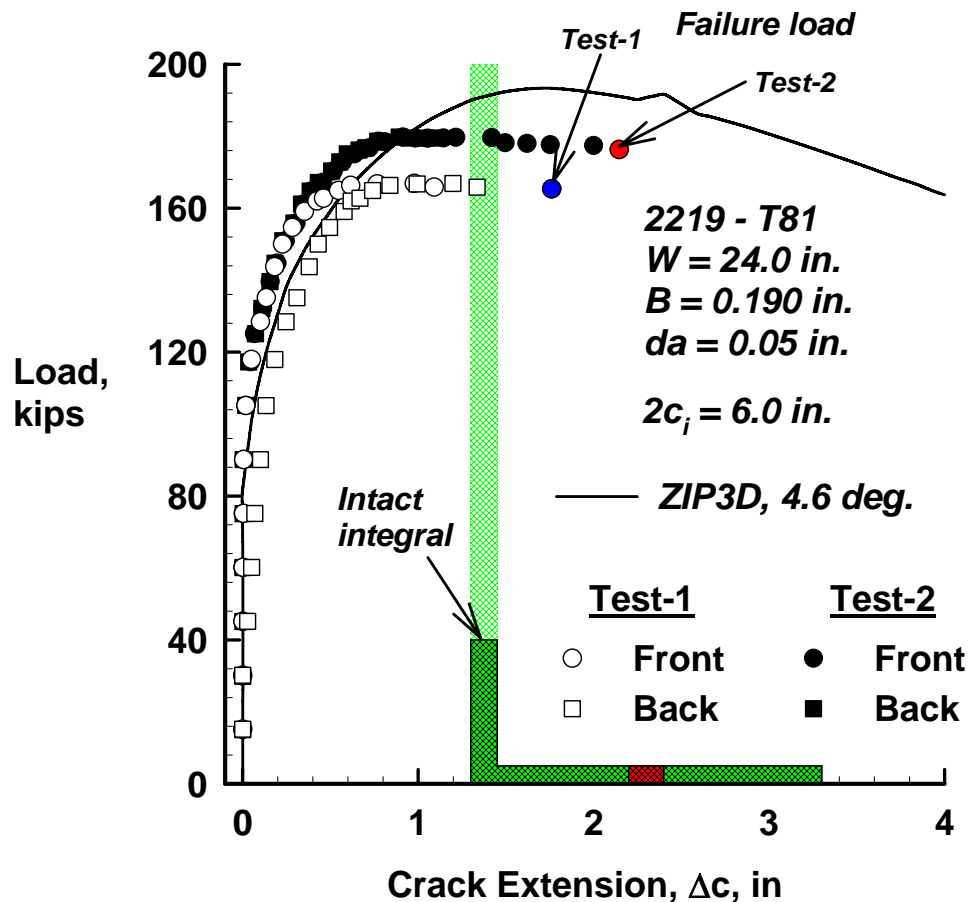


**Residual Stress Distribution in Friction Stir Welded Aluminum alloy**

# ZIP3D Finite Element Model of 24-inch Wide FSW Residual Strength Panel



# Load Crack Extension data for 24-inch Wide FSW Panel



# Concluding Remarks



- **The prediction methodology estimated the residual strength of both built-up and integrally machined 24-inch wide panels within 5.0 % of test.**
- **The analysis predicted the residual strength of FSW and EBF3 panels within 10 % of test data.**
- **The analysis results indicate a robust prediction methodology based on CTOA concept is able to characterize varying integral configurations fabricated using different manufacturing procedures.**
- **The panels will be reevaluated for residual strength after obtaining the residual stress field and stress-strain curve for the heat effected zone material.**
- **The analysis methodology demonstrated potential for use in future design of integrally stiffened aerospace structures.**